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Real Dust Particles and Unimportance of the Poynting-Robertson Effect

M. Kocifaj [1)] **and J. Klačka** [2)]

Institute of Astronomy, Slovak Academy of Sciences, Dúbravská cesta 9,

842 28 Bratislava, Slovak Republic [1)]

Institute of Astronomy, Faculty for Mathematics and Physics, Comenius University

Mlynská dolina, 842 15 Bratislava, Slovak Republic [2)]

Abstract. The importance of the Poynting-Robertson effect on the motion of interplanetary dust particles is discussed. Precise numerical calculations for real dust particle show that condition for the validity of the Poynting-Robertson effect is not fulfilled. The interaction of the (solar) electromagnetic radiation with really shaped dust particle is different from that which yields the Poynting-Robertson effect. The magnitude of the Poynting-Robertson effect's deceleration term is in one to two orders in magnitude (it depends on particle's size) less important than terms corresponding to nonforward (or, nonbackward) scattering.

1. Introduction

The Poynting-Robertson effect (P-R effect) (Robertson 1937; Klačka 1992a – the most complete form of the P-R effect) is generally considered to be the real effect which causes inspiralling of interplanetary dust particles (IDPs), meteoroids, toward the Sun. (Other, more simple correct derivations may be found in Klačka's papers: 1992b, 1993a, 1993b). The most general case of the validity of the P-R effect requires that Eq. (120) (or, Eq. (122) for the moving particle) in (Klačka 1992a) holds. This may not be the case for the real nonspherical particle, as it was discussed in Klačka (1993c, 1993d (some numerical errors, which may be easily found, are in the last section; moreover, real particle should rotate around one axis – axis of rotation; the important result is that the significance of the transversal components increases with increasing porousity and reflectivity of dust particle), 1994b) and applied in Klačka (1994a).

General equation of motion of IDP in terms of optical properties was presented by Klačka and Kocifaj (1994) – the paper does not present any quantitative calculation for real particles.

The aim of this paper is to present quantitative results for real stationary (not moving around the Sun) IDP.

2. More Detailed Qualitative Discussion

Interplanetary dust particles are different in size, chemical composition, shape and physico-optical properties. The light scattering by such particles predetermines changes of their motion in the space. This fact is expressed by well-known radiation pressure, which was notoriously based on spherical target assumption. Scattering diagram for spheres shows the radial symmetry in Sun-particle coordinated system. The only forward and backward scattering efficiences are important in this case. However, any irregularity of the particle shape will produce certain momentum in perpendicular projections to the direction of light propagation. This may be caused also by inhomogeneity of particle chemical composition (or particle density). Particle shape specificity (unconcavities, cavities,...) play dominant role in formation of light scattering diagram. Several studies on nonspherical particles start with model types of particles such as ellipsoids, cylinders, rectangular targets. However, this approach must allways take into account a certain degree of particle shape symmetry, which is responsible for decreasing of light intensity scattered to the perpendicular directions. Really shaped particle is therefore the best candidate to make an appropriate conclusions. We are using the computer model of real cosmic dust particle U2015B10 (Clanton *et. al*, 1984).

3. Model particle

The computer model of the really shaped particle is practically identical with the catalogued cosmic dust particle U2015B10. The only total size (radius of an equivalent sphere) was modified to reach required conditions for theoretical study (to enable perform the calculation of scattering effects by wide particle population). Computer model was based on scanning of particle by electron microscope. The particle consists mainly from Mg, Al, S, Ca and Fe. We have also found that enstatite, constitution of which is near to

$Mg_{0.8}Fe^{II}_{0.2}SiO_3$, dominates in particle composition. From the morphological point of view, it is remarkable that the U2015 B10 sample has probably a cavity in its center (for the further details see Kapišinský *et al.* , 1995). Since the mineral enstatite is dominant in composition of U2015B10, the mean refractive index of the particle can be, in sufficient accuracy, fitted by the enstatite optical properties ($n_r = 1.735 - 0.26\lambda$, $n_i < 10^{-4}$). The values n_r and n_i represent the real and imaginary part of particle refractive index, respectively. Detailed description of the model and its setup characteristics for calculation are discussed in (Kocifaj *et. al*, 1999).

4. Calculation method

The characteristics of radiation scattered by examined cosmic dust particle were calculated using the so-called Discrete Dipole Approximation (Draine, 1988). Particle effective radius was 0.5 μm while the wavelength of an incident radiation cover the visible spectrum and near infrared spectral band (i.e., the spectral range which corresponds to the maximum energy distribution in solar spectrum). The mean direction of propagation of the scattered radiation is characterized by vector $\boldsymbol{g}$

$$\boldsymbol{g} = < \cos\theta_s > \boldsymbol{x} + < \sin\theta_s \cos\phi_s > \boldsymbol{y} + < \sin\theta_s \sin\phi_s > \boldsymbol{z} , \tag{1}$$

where θ_s and ϕ_s represent the scattering angle and azimuth measured around the axis $\boldsymbol{x}$ characterizing the direction of propagation of the incident radiation. The radiative energy scattered to the directions perpendicular to $\boldsymbol{x}$ (i.e., $\boldsymbol{y}$ and $\boldsymbol{z}$) are expressed by the last two terms. They are corresponding to the parameters G_1 and G_2, while G_0 belongs to the first term, using the formalism utilized in Kocifaj and Kapišinský (1997). The P-R effect may be unappropriate if ratios G_x/G_0 ($x = 1, 2$) are greater than $\approx 10^{-4}$. Rotation of the particle in the space can decrease the ratios by averaging over the whole solid angle. Average value of the parameter G can be expressed as follows:

$$< G > = \frac{1}{8\,\pi^2} \int_0^{2\,\pi} d\beta \int_{-1}^{1} d\,\cos\theta \int_0^{2\,\pi} G(\beta, \theta, \phi)\, d\phi, \tag{2}$$

where β, θ and ϕ are angles which represent the particle orientation in the lab-frame (Draine and Flatau, 1996). The target is oriented such that the polar angles θ and ϕ specify the direction of a selected unit vector in the particle relative to the incident radiation. The target is assumed to be rotated around this unit vector by an angle β.

Averaging in wavelengths is defined by the following equation:

$$< \boldsymbol{g}_{integr} > = \int_{\lambda_1}^{\lambda_2} I_0(\lambda)\, \boldsymbol{g}\, d\lambda , \tag{3}$$

where $I_0(\lambda)$ is intensity of the incident radiation.

5. Results

The mean values of individual components of the vector $\boldsymbol{g}$ depend on the particle orientation in the laboratory frame. Averaged values of ratios G_x/G_0 for rotating particle are functions of orientation of the rotation plane (or axis of rotation). The examined ratios will be very small for particles with a relatively small asymmetry when cross section varies slowly during rotation (e.g., axis of rotation is parallel to the direction of the incident radiation). We have studied rotation in three planes, when two angles from β, θ, or ϕ are constant and one of them varies over whole possible range. It is evident that rotation with the variable angle ϕ brings very small values of ratios G_x/G_0. This is caused by practically constant cross section in all particle positions (the changes of angle ϕ express the precession of the particle in our case). Results of calculation for monochromatic radiation and polychromatic radiation are presented in Tables 1 and 2. Rotation of the particle derived from the monotonous change of the angle β, or θ, brings the fluctuation of the particle cross section. This fact results in an asymmetry of the radiation scattering diagrams. Such a case indicates an increase of ratios G_x/G_0. Calculated data summarized in Table 1 confirm high value of these ratios (about 0.02-0.07).

Integral values presented in Table 2 were obtained by integrating $\boldsymbol{g}$ over the studied spectral band from $\lambda = 0.5$ μm to $\lambda = 0.9$ μm. Radius of the particle was 0.5 μm. The ratio G_x/G_0 is at level 10^{-2} which is in two magnitudes greater than the limit value of 10^{-4}. The results for the 5.0 micron particle (radius = 5.0 μm) are approximately 20-50 times less than values given above, i.e., the ratio is still not less than 10^{-4}. It means, the submicron and small micron particles violates the limit value of 10^{-4}. Scattering diagrams presented in Figures 1-3 show the distribution of the energy scattered in the halfsphere outward the Sun (i.e. in direction of incident radiation). Wavelength of the incident radiation was 1.0 μm in this case. However, the isolines are asymmetric for θ and β also after integration over all particle orientations during rotation and over all used wavelengths. It is important result. It characterizes the real influence of particle shape on the resulting motion of the particle in the space. The values of individual isolines vary only over two magnitudes – this is the reason why the ratios G_x/G_0 are so important. Figure 3 presents the resulting scattering diagram after integration over all particle positions derived from changes of angle ϕ. This diagram is completely identical to the scattering diagram for the sphere. It documents that the rotation of the particle may significantly decrease the relatively high values of the examined ratios (Table 1). It also documents the level of numerical precision of the calculation. Results for the other types of rotation

Table 1. Spectral radiation characteristics calculculated at selected wavelengths

rotation of the particle derived from monotonous change of angle β

λ [μ m]	G_0	G_1	G_2	G_1/G_0	G_2/G_0
0.50	1.231	0.094	-0.003	0.076	-0.003
0.56	1.219	0.097	0.003	0.080	0.002
0.64	1.205	0.094	0.001	0.078	0.001
0.75	1.156	0.098	-0.003	0.085	-0.003
0.90	1.056	0.082	-0.002	0.078	-0.002

rotation of the particle derived from monotonous change of angle θ

λ [μ m]	G_0	G_1	G_2	G_1/G_0	G_2/G_0
0.50	1.270	0.030	-0.042	0.023	-0.033
0.56	1.301	0.036	-0.054	0.028	-0.042
0.64	1.288	0.049	-0.015	0.038	-0.011
0.75	1.279	0.047	0.046	0.037	0.036
0.90	1.128	0.029	0.087	0.026	0.077

rotation of the particle derived from monotonous change of angle ϕ

λ [μ m]	G_0	G_1	G_2	G_1/G_0	G_2/G_0
0.50	1.477	-0.000	0.000	0.000	0.000
0.56	1.454	0.000	0.000	0.000	0.000
0.64	1.366	0.000	-0.000	0.000	0.000
0.75	1.315	0.000	0.000	0.000	0.000
0.90	1.123	-0.000	-0.000	0.000	0.000

(expressed in terms of angles β and θ) show that one component of G_x/G_0 is preferred. The ratio G_1/G_0 (axis $90^o - 270^o$) is greater than G_2/G_0 (axis $0^o - 180^o$) for the rotation derived from changes of the angle β (Fig. 2) – partial symmetry of the scattering diagram over the axis ($0^o - 180^o$) is evident. The importance of one of the components G_x/G_0 predetermines the acceleration of the particle in the defined direction. Moving the particle to the other position relatively to the Sun can bring a change of the preferred direction

Table 2. Integral values of radiation characteristics G averaged over visible spectrum

angle	G_0	G_1	G_2	G_1/G_0	G_2/G_0
β	0.670	0.054	-0.000	0.080	-0.001
θ	0.720	0.023	0.001	0.033	0.001
ϕ	0.770	-0.000	0.000	0.000	0.000

of motion due to a possible new lab-frame conditions. The particle may be accelerated only during a limited time. Another position of the particle with respect to the Sun may decelerate its motion.

6. Conclusion

We have shown that real dust particles may exhibit important nonforward and non-backward scattering efficiences in comparison with the result when the P-R effect holds. Therefore, the P-R effect cannot be simply applied to the study of a particle motion in space without precise physico-optical analysis.

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Figure caption

Fig. 1. Scattering diagram for the particle rotation derived from monotonous change of the angle θ. Source of radiation (Sun) is behind the centre of the picture. The azimuth angle ϕ_s is displayed on the border of the diagram.

Fig. 2. Scattering diagram for the particle rotation derived from monotonous change of the angle β. Source of radiation (Sun) is behind the centre of the picture. The azimuth angle ϕ_s is displayed on the border of the diagram.

Fig. 3. Scattering diagram for the particle rotation derived from monotonous change of the angle ϕ. Source of radiation (Sun) is behind the centre of the picture. The azimuth angle ϕ_s is displayed on the border of the diagram.

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